Quantum Information Storage in Silicon

Using an ultrapure, isotopically enriched silicon crystal made by LBNL, a team of Oxford and Princeton scientists has demonstrated storage of quantum information in the solid state. As described in the October 23 2008 issue of *Nature*, the information was processed, stored in a quantum state of an atomic nucleus, and then read back. This is the first demonstration that a single atomic nucleus can serve as quantum computational memory.

In classical computing, information is processed and stored in "bits" with values 0 or 1 (magnetic, as on a hard drive; voltage [high/low] as in computer chips; or reflective or non- reflective spots, as on a CD). The spin of an electron, which, in a magnetic field, can point "up" or "down," can also encode data in 0s and 1s. Electron spin however, has the additional ability to be both up and down at the same time, due to a quantum effect known as "superposition." Superpositioning exponentially expands the storage capabilities of a so-called quantum data bit or "qubit." Whereas a byte of classical data made up of three bits can represent only one of the eight possible combinations of 0s and 1s, a qubit can represent all eight combinations at once. Furthermore, operations on all eight combinations can be performed simultaneously.

If a quantum computer could be realized, certain mathematical tasks, such as factoring, could be performed many billions of times faster than they are on the most powerful supercomputers of today. Many challenges stand in the way of the development of quantum computing however, one of which is the identification of a mechanism to preserve the integrity of data while it is stored. This requires that the "coherent" relationship between the qubits be maintained so that the results of the calculation are not lost. While electron spins have been used as qubits for a number of small scale demonstrations of quantum computation in the solid state, they may be too fragile to be used as memory–the data quickly becomes corrupted by the influence of other electrons.

To overcome this obstacle, the team turned to the more protected environs of the atomic nucleus. Individual phosphorus (^{31}P) atoms embedded in bulk silicon (^{28}Si) could be ideal for quantum information storage as they have both an electron spin (P has one more valence electron than Si) and a nuclear spin (^{31}P, the only stable isotope of P, has an odd number of nucleons). Nuclear spins are well-suited for memory, as their coherence times can be very long. However, natural silicon contains 4.7% of the ^{29}Si isotope, which also has a nucleus with spin and this would quickly destroy any coherent state made with the P atoms. Joel Ager and Eugene Haller at LBNL's Electronic Materials Program provided the solution to this problem, making ultrapure silicon crystals in which nearly all of the ^{29}Si had been removed, and, after additional steps of chemical purification, had just the right amount of phosphorus (too much and the P spins interfere with one another, too little and the signals are too weak to detect).

The LBNL crystals were studied at Princeton in a electron spin spectrometer at temperatures near absolute zero. A coherent electron state was created in the P electron spins (prior Princeton/LBNL work has shown that this lasts only a few milliseconds), transferred to the P nuclear spin by a sequence of radiofrequency and microwave pulses, then transferred back and read out. By varying the time between the first transfer and the final readout, it was shown that the information retained its fidelity for over 1 second, hundreds of times longer than it could with the electrons alone.

Now that it has been demonstrated that electron spin data can be stored and retrieved via nuclear spin, future steps will require improving spin control and readout mechanisms. Also, while the quantum memory time observed in this study is exceptionally long by previous standards, research is focused on extending it further.

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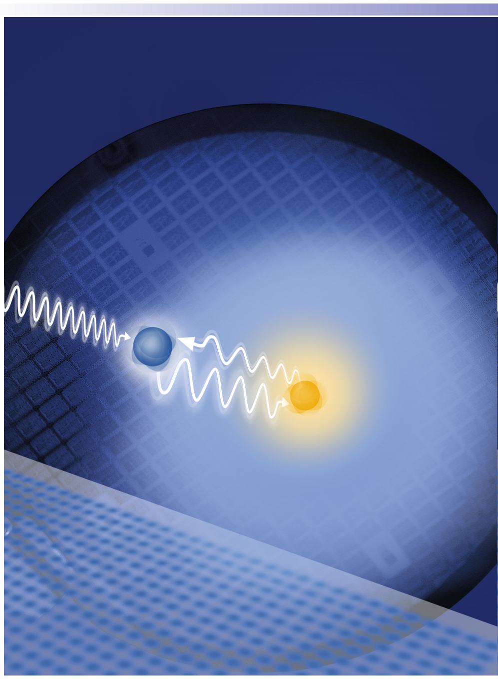
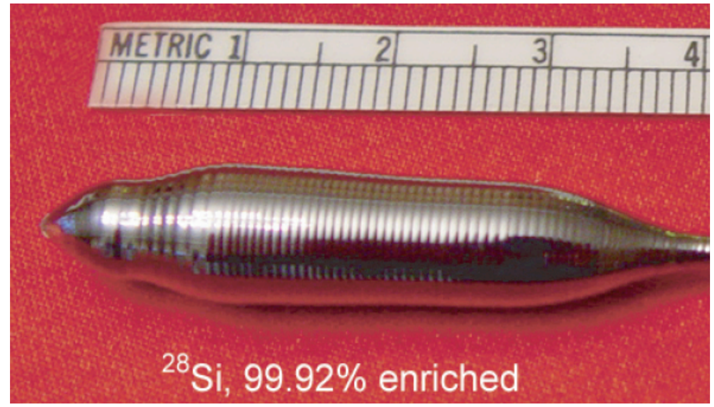
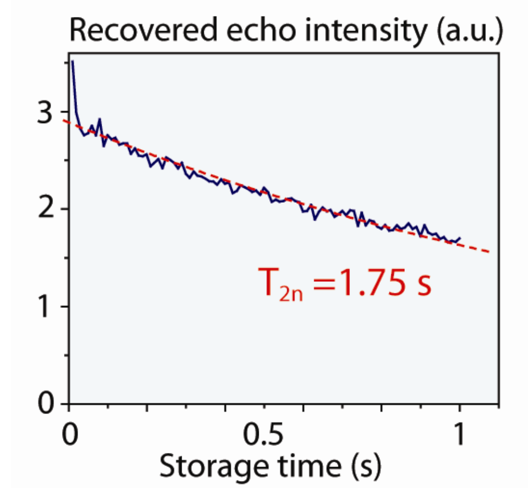
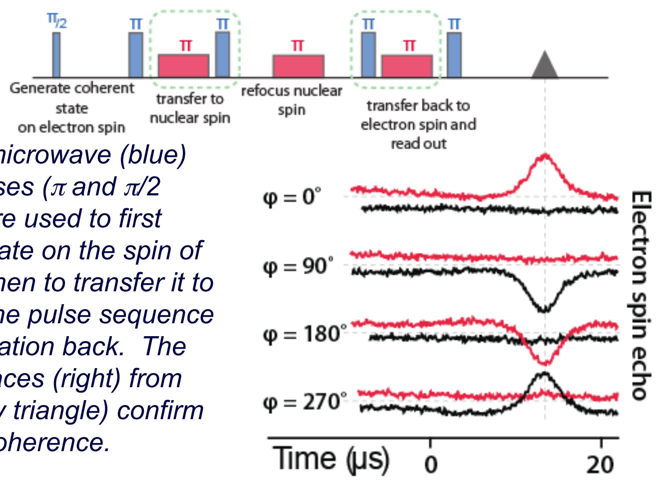


LBNL silicon single crystal *(right) enriched in ^{28}Si, with nearly all of the ^{29}Si (4.7% nat. abundance) removed. The optimal P content (too much and the P atoms interact with one another, too little and the signal cannot be detected) was achieved by five passes of zone refining followed by floating zone crystallization.*



Schematic of the quantum information storage method *(left). Quantum information encoded on the electron spin (blue) is stored on the nuclear spin (yellow) of phosphorus atoms through a combination of microwave and radio-frequency pulses. The sequence is reversed for read-out.*





A sequence (above right) of microwave (blue) and radiofrequency (red) pulses (π and $\pi/2$ indicate the pulse duration) are used to first create a coherent quantum state on the spin of the electron bound to P and then to transfer it to the P nucleus. After 50 ms, the pulse sequence is reversed to read the information back. The out of phase red and black traces (right) from the resultant "spin echo" (grey triangle) confirm the preservation of the spin coherence.

The amount of time between the write and read pulse sequences was varied to determine how long quantum information could be stored. The memory storage time is limited by the decoherence time of the P nuclear spin and is nearly 2 seconds in this experiment. Using the electron spin alone would yield a storage time 350x shorter.